A Structured Approach to RLV Technology Flight Testing

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Abstract

A team of reusable launch vehicle (RLV) technology experts has developed a Phased Development Approach (PDA) using Integration Readiness Levels (IRLs) to facilitate selection, sequencing and staging of flight test demonstrations to reduce the risks inherent in technology development. This approach, which focuses on both component technologies and the flight vehicle system, is shown to correspond with the likelihood of meeting mission objectives. Technology Assessment and Flight Option databases are provided for use with the PDA, and a "flight filter" is included as a guide to determine if flight or ground testing would be most effective. Guidelines derived from past flight demonstration programs, used to refine the PDA, are also provided.

Introduction

Over the past 20 years, NASA and the Department of Defense have conducted a number of RLV demonstration programs with varying degrees of success. In an attempt to better understand the underlying causes for the mixed performance, NASA partnered with representatives from several Air Force Commands to identify and describe the processes used to plan, support and conduct RLV demonstrations. By examining past development programs and capitalizing on successful approaches, the team developed a structured approach to technology development and flight demonstration program definition. This approach limits risks by incorporating proven technologies into ground and flight tests as the flight vehicle is developed, thereby reducing the variables and risks associated with launching the final mission vehicle.

Methodology Development

A diverse team of vehicle and technology experts from NASA, the Air Force Space Command (AFSPC), which includes the Air Force Space and Missile Command (SMC), and the Air Force Research Labs (AFRL) was formed to conduct this study and publish these recommendations. The recommended development approach is based on results of previous RLV technology development and testing programs. Key elements of this approach have been used in development programs, but a formal approach combining and sequencing the key elements has not been defined until now.

In addition to gathering past RLV program documentation – including program plans, test plans and, where available, test reports – the team collected input from RLV program officials. These experienced program leaders were asked to assess which aspects of these programs contributed to their successes or challenges. The detailed logic from this investigation is incorporated into Appendix A, "A Structured Process for Implementing a PDA Technology Development Program." Appendix B is the Technology Assessment Database, and Appendix C is the Flight Options Database, both referenced in the PDA model. Appendix D lists the members of the study team and the organizations they represent.

The Phased Development Approach

The PDA model, depicted in Figure 1, has four key steps, or phases. Phase 1 is the basic laboratory research and testing of concepts and component technologies. Phase 2 involves selected flight or ground demonstrations focusing on the tested technologies. Flight tests at this phase are often flown "piggy back" on an existing flight system, thereby reducing the risks associated with testing the component technologies concurrently with an experimental flight vehicle. Phase 3 combines the component technologies into a system demonstration vehicle – commonly called an X-vehicle – to test the integration of the components. Phase 4 is the final development of a new operational vehicle based on the proven technologies and system demonstrations.

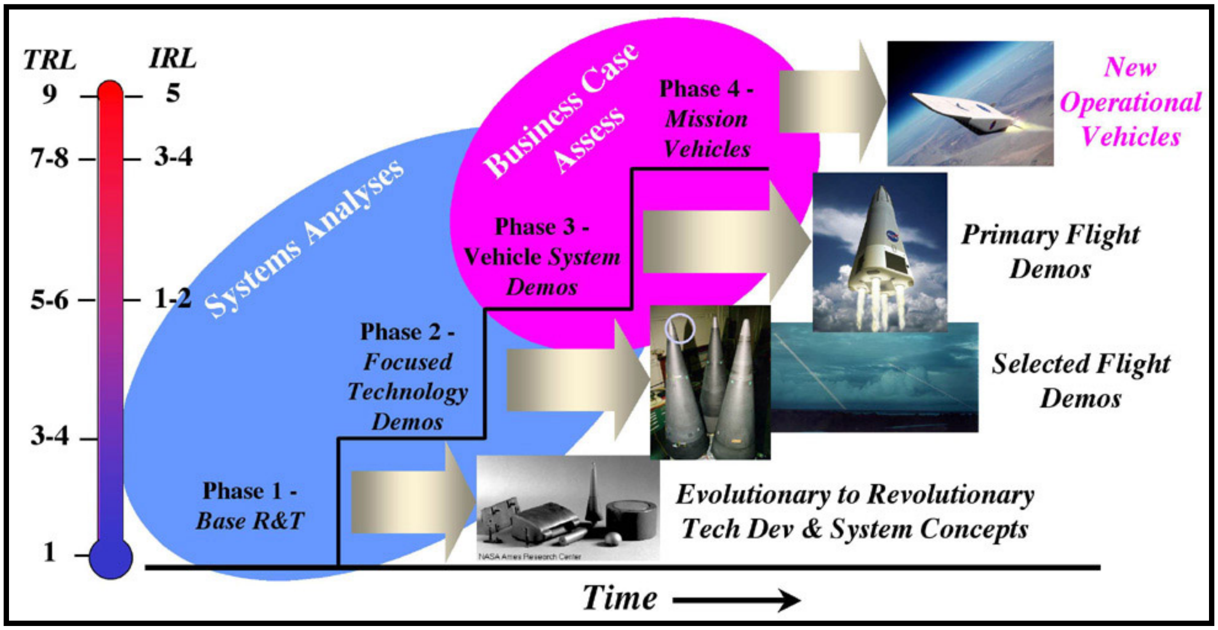


Figure 1: The Phased Development Approach (PDA) for Technology Maturation

The PDA model uses both the standard Technical Readiness Level (TRL) and a new Integration Readiness Level (IRL), defined in Figure 2-A, to gauge the maturity of technology components and the vehicle system integration. Figure 2-B shows the relationship between TRL and IRL. These measures are used to help establish the appropriate phase and activities for each development step. The IRL assessment was introduced to measure a technology's system-integration readiness for a given application in much the same way TRL assessment measures the readiness of individual technology components. IRL assessment has been used in commercial industry for modular software development to ensure that programs and systems operate as intended when new versions are compiled. Although the concept of integration readiness has been applied in past development programs, this PDA model is the first formal application of IRL assessment in hardware development. Examples of integration readiness are included in Appendix E.

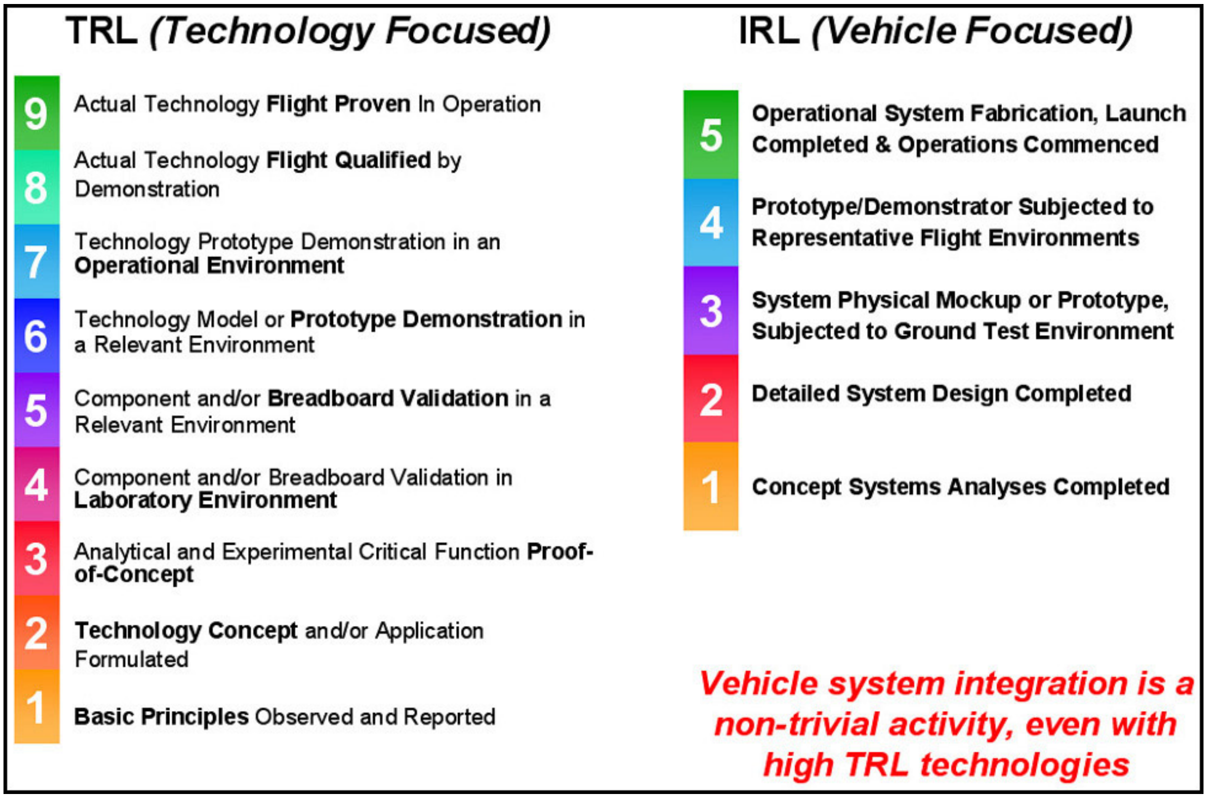


Figure 2-A: Technical and Integration Readiness Level Definitions

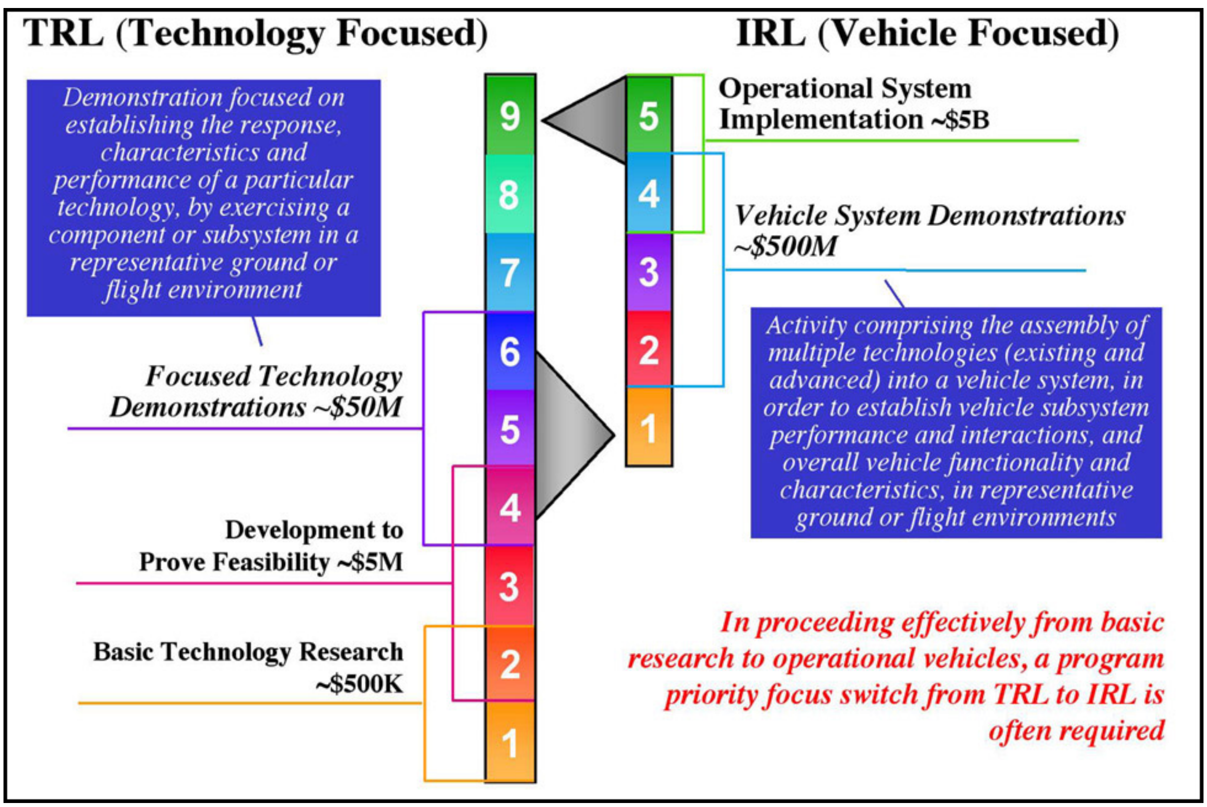


Figure 2-B: Relationship Between Technical and Integration Readiness Levels

A critical element of the PDA, commonly omitted from non-phased development programs, is technology demonstration. This Phase 2 activity provides critical technology maturation and product cycles to help ensure the success of system demonstrations. Technology demonstrations are much less expensive than system demonstrations, and the flight tests can often be flown on proven vehicles, greatly reducing the risk of flight failure. This is because the risks associated with the low TRL of the demonstration technologies are mitigated by the high IRL of the host system. Some examples of Phase 2 Focused Technology Demonstrations are shown in Table 1.

Demonstration of X-33 Vehicle Health Management System Components on the F/A18 System Research Aircraft NASA
X-ACT: CRV Actuator Test on a F-15
X-38 used the F-16 VISTA
X-38 flew its SIGI on the Lear POC
X-34 flew its INU on a C-10 at Holloman
UCAV used the T-33 as a surrogate
B-52 test of Space Shuttle SRB Recovery System and Shuttle Parachute System (Qualified systems)
Convar 990 test of Shuttle main landing gear, tire and brake testing (resulted in changes to vehicle and runways)
F-8 test of Shuttle Flight Software Test, Solved PIO (Pilot Induced Oscillation) problem (a big issue before the first launch, discovered during the approach and landing test after dropping the shuttle off the back of the 747)
F-104/F-15 test of Shuttle Tiles, discovered significant problems when flown in simulated rain
IRIDIUM Hardware flown on the SR-71 (Qualified hardware for launch)
OSC Hardware Flown on the SR-71
LASRE flown on SR-71 (canceled before Aerospike Engine could be hot fired in flight due to system safety & budget issues)

Table 1: Examples of Phase 2 Focused Technology Demonstrations

Guidelines for RLV Technology Development & Flight Testing

These guidelines are intended to help the user consider approaches to maximize program effectiveness and minimize risk. They will not, however, dictate the development approach for the user. The use of these guidelines should help refine planning and improve the likelihood that technology test flights will meet mission objectives while yielding cost-effective technology development projects.

- Technologies should be matured using a Phased Development Approach, which considers both Technology Readiness Level (TRL) and Integration Readiness Level (IRL), as defined in Figure 2-A.
- In general, a low-risk flight test should incorporate technologies with high TRLs (6 or greater) for flight-critical components. This is especially critical when multiple new technologies are to be tested together in a new vehicle system.
- Flight demonstrations of advanced, flight-critical components at moderate TRLs (4-5) should be pursued on a “one technology per flight test” basis (Focused Technology Demos), on high IRL (4 or greater) systems where possible. Technologies at low TRLs (below 4) need to be matured at the laboratory and ground-test level before being considered for flight testing.
- The flight filter logic (defined in Appendix A, Figure A-1) should be used as a guide to determine if flight or ground testing is most effective at the current maturation level of a given technology.

Generally, a flight test vehicle should have high TRL technologies, be at a high IRL or both to have the greatest chance for success. An exception is when a demonstration technology is flown in a truly non-flight-critical manner. Another key to minimizing flight-test program risk is to introduce only a small number of advanced flight-critical technologies at each stage of vehicle development. A more formal process for evaluating technologies for potential flight testing is presented in Appendix B.

Methodology Evaluation

To evaluate the effectiveness of using the PDA model, the study team examined all X-vehicle programs focusing on RLV development for which data were available. The team reviewed documentation and program office assessments and also made independent assessments of targeted technologies' TRLs and IRLs in each program. Of particular interest were those technologies flown in a flight-critical manner. Next, past X-vehicle programs were evaluated against their stated mission objectives using the PDA model and logic; results are listed in Table 2. The method correctly predicted the historical results.

Vehicle	Overall TRL	IRL	Phase	Completed Mission Objectives
DC-X	6-9 (high)	1+ (Sys Concept)	3 (Sys Demo)	Yes
DC-XA	1-5 (low, composite LOX cryo tank)	4 (Prototype flown)	2 (Focused Tech Demo)	Yes
X-33	1-5 (low)	1 (Sys Concept)	3 (Sys Demo)	No
X-34	1-5 (low)	1+ (Sys Concept)	3 (Sys Demo)	No
X-36	6-9 (high)	1-2?	3 (Sys Demo)	Yes
X-37	1-5 (low)	1 (Sys Concept)	3 (Sys Demo)	TBD
X-38	6-9 (high)	1-2?	3 (Sys Demo)	TBD
X-40	6-9 (high)	1-2?	3 (Sys Demo)	Yes
X-43A	4-9 (medium)	2 (Detailed Design)	3 (Sys Demo)	TBD
X-43A-LS	6-9 (high)	1-2?	3 (Sys Demo)	Yes

Table 2: TRL/IRL/Phase Assessment for Historical Vehicles

A graphical display of the TRL/IRL data from Table 2, along with an assessment of mission success, is shown in Figure 3. Green indicates success; yellow indicates pending assessment; red indicates completion short of mission objectives. Systems with overall high TRLs and low vehicle IRL tended to be successful. Systems with low TRL components employed on an existing, high-IRL vehicles also tended to be successful. Systems with overall low TRLs and low vehicle IRLs tended to be unsuccessful.

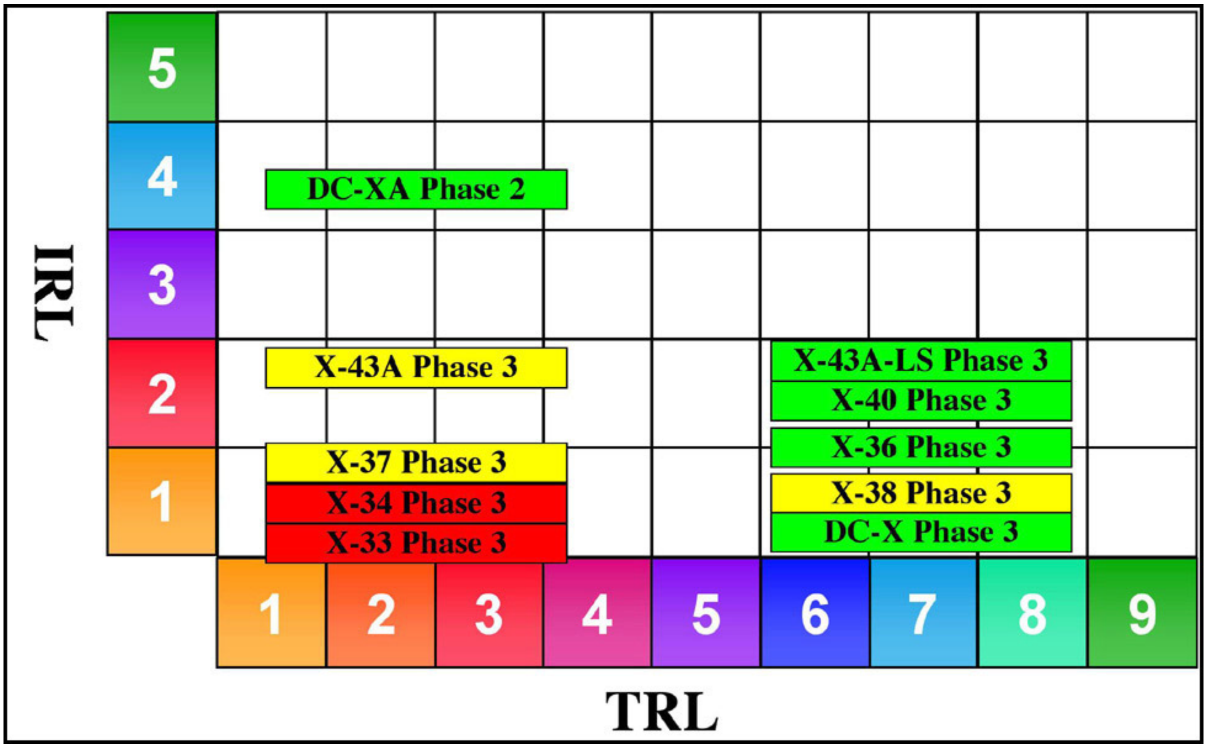


Figure 3: TRL/IRL Historical Vehicle Assessment

Conclusions

In developing the PDA model, the study teamed identified several benefits to employing a phased approach to RLV development. Primarily, the PDA model distributes the inherent risks of system development across multiple program phases, thereby reducing the risk and high cost of system failure at the final stage of development. Phased development also provides opportunities to select the most successful and mature technologies at each phase – technologies that could be applied to other systems and industries at the component level. And finally, phased development creates product cycles, which are critical for developing a knowledgeable workforce and overall organizational competence. Based on the historical analysis of successful X-vehicle missions and the additional benefits generated by phased development, the PDA model warrants serious consideration for RLV and other systems development programs.

APPENDIX A

A Structured Process for Implementing a PDA Technology Development Program

This appendix describes a detailed, structured process for effectively implementing a PDA development program.

Before approaching the logic flow charts, the user should answer the following questions:

1. What are minimal mission requirements?
2. What are the vehicle system concepts for meeting these mission requirements?
3. What technologies are required for these vehicle concepts?
4. What are the TRLs for the technologies to be developed? (The TRL definition in Figure 2-A can help determine TRLs.)
5. What is (are) the IRL(s) for the vehicle concept(s) to be developed? (The IRL definition in Figure 2-A can help determine IRLs.)

A user who plans to integrate one or more technologies onto a test vehicle must satisfactorily answer all five questions. Answering the last two may be sufficient for a technology developer.

Once these questions have been answered, the user is ready to address the PDA Technology Development Logic shown in Figure A-1.

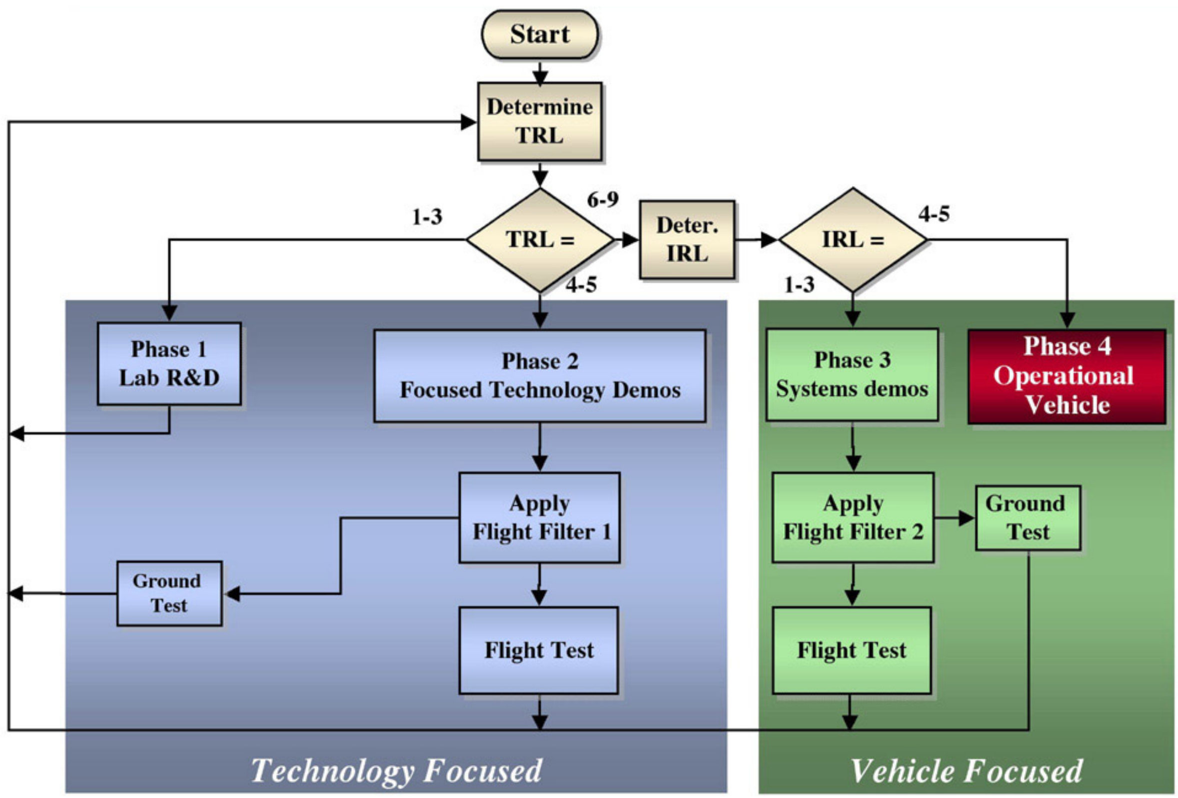


Figure A-1: PDA Technology Development Logic

The PDA process flow proceeds as follows:

- For technologies below TRL 4, pursue additional laboratory research and technology development (Phase 1) before attempting ground or flight demonstrations.

- For technologies at TRL 4-5, identify focused technology demonstrations (Phase 2) to advance technologies to TRL 6. Use the flight filter logic in Figure A-2 to establish which demonstrations require flight. A Technology Assessment Database (Appendix B) and a Flight Options Database (Appendix C) have been developed to help with the flight filter assessment.
- For technologies TRL 6 and above, identify vehicle system demonstrations (Phase 3) required to advance to TRL 8 and IRL 4. Again, use the flight filter to establish which of these demonstrations require flight testing.
- Return to the top of the PDA Technology Development logic flow and repeat this process until all flight technologies are at a TRL of 8 or greater and all vehicle concepts are at an IRL of 4 or greater – at which time the program is ready for operational vehicle activities (Phase 4).
- The flight filter shown in Figure A-2 is an important element of the PDA process. This filter is intended to establish when flight testing is required or beneficial. The key question to establish whether or not flight testing is required is shown in the first logic block in Figure A-2: "Are relevant test environments available on the ground?" The answer requires examination of the technology under consideration, its TRL and the important drivers impacting its development and eventual use. Technologies requiring combined or variable environments to establish their response and behavior, for example, or technologies that put human safety at issue, often require flight testing at some point in their development. There are also cases where flight testing may be more cost effective than ground testing. The second logic block in Figure A-2 addresses this situation. The Technology Assessment Database described below provides more specific information and examples relative to establishing flight requirements.

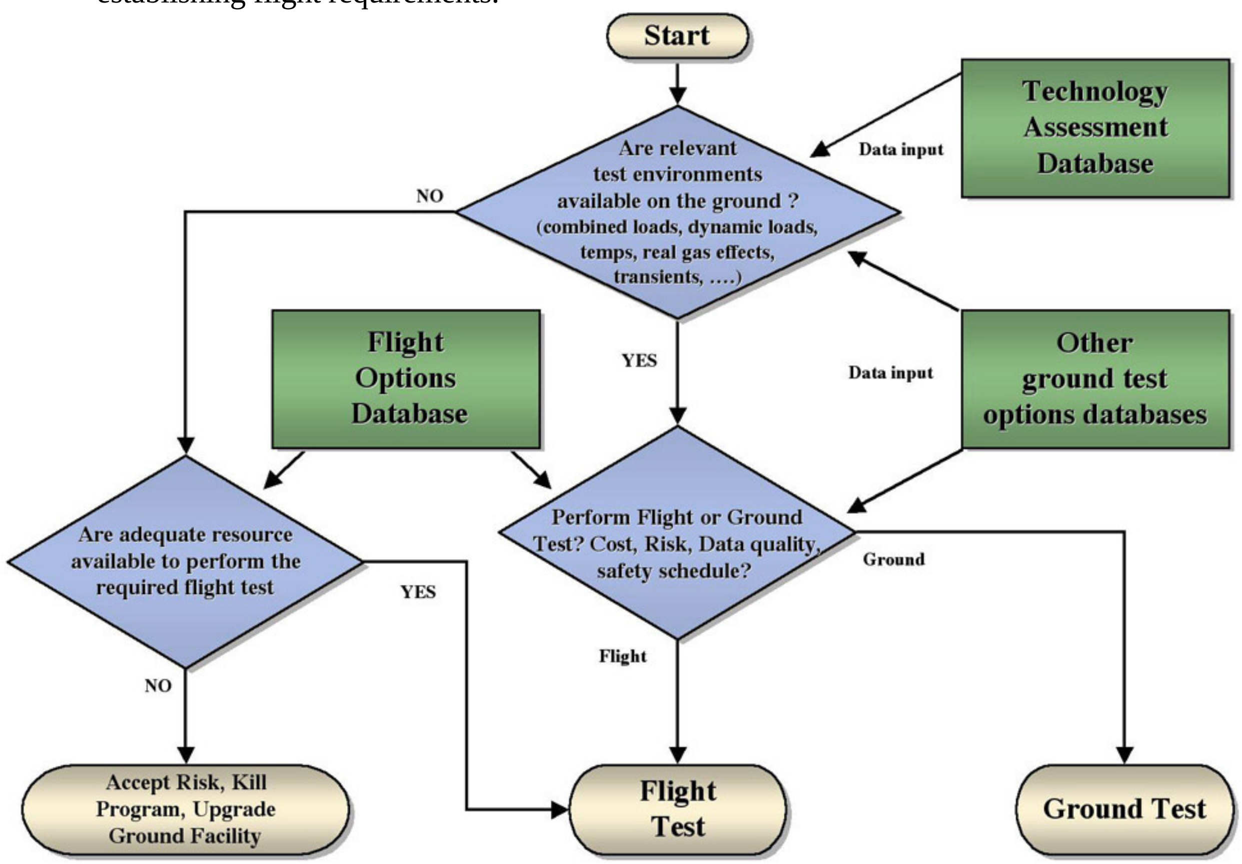


Figure A-2: Flight Filter Logic

It is important to carefully consider TRL assessments when technology applications change from initial usage, such as when flight-proven components are used in a new environment in which they have not been certified. It is also important to define IRLs in the context of the proposed flight demonstration vehicle systems.

This study generated two databases to assist in determining which flight demonstrations to pursue and to provide options for those demonstrations. These databases are briefly described below and presented in their entirety in Appendices B and C.

Technology Assessment Database

In assembling the Technology Assessment Database, the study team leveraged several existing technology requirement databases, including current databases from the Second Generation and Third Generation Reusable Launch Vehicle programs and the Military Spaceplane (MSP) and Reusable Launch Vehicle Study, as well as other earlier and related programs.

The database (Appendix B) was assembled in Microsoft Excel; a worksheet sample is shown in Figure A-3. The intent was to identify common vehicle technology categories and assess their relative maturity and potential flight demonstration requirements. The database includes the technology category name, description and characteristics, vehicle application and current TRL.

For reference, the database also includes a general assessment of whether flight demonstration is required, as well as a flight-testing benefit index. For technologies assessed as requiring flight testing, the data includes a designation of type (focused demonstration, system demonstration or both) along with a justification and approximate scale required.

X-Vehicle Team Technology Assessment Worksheet, 5/10/02

Technology Categories	Description/Characteristics	Applications	Reference: approx 2002 TRL	Eventual Flight Demos Required ?	Flight Demo Benefit Index (0-none to 5-significant)	Justification	If Yes, Focused Technology or Vehicle System Demos
Analyses (Rasky)							
Systems Engineering & Architecture Definitions	System engineering and analyses defining architectures, vehicle concepts, vehicle technologies and operations models	All advanced vehicle development programs	5	No	0	Ground activity	
Structures/TPS (Kolodziej, D. Glass, Brunty)							
TPS, Sharp Leading Edges	Small radius (r < 1cm) leading edges for nosetips, wings, and control fins. New, durable sharp leading edge assemblies designed for maintainability.	Enabling for high L/D Earth to Orbit (ETO) and crew return vehicles with improved abort and safety. Enabling for all airbreathing vehicles.	2-5	Yes	5	Representative combined aerothermal, aerodynamic and natural environments cannot be adequately produced in ground facilities or with analyses for sharp leading edge components	Both
TPS, Blunt Leading Edges and Nosecaps	Large radius (r > 1 cm) leading edges for for nosetips and wings. Improved, durable blunt leading edge assemblies designed for maintainability.	Medium L/D Earth to Orbit (ETO) cargo and crew return vehicles with Shuttle class abort and safety requirements.	4-6	No	4	Combined aerothermal, aerodynamic and natural environments provided by flight would be very beneficial for development	Both
TPS, Acreage Surfaces	Flight weight external insulation on large areas of the windward and leeward surfaces that is shaped to define the vehicle aerodynamics. Durable tiles, panels, blankets, or felts designed for maintainability. Typical windward TPS has higher temperature and strength capability than leeward TPS.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-7	No	4	Combined aerothermal, aerodynamic and natural environments provided by flight would be very beneficial for development	Both
TPS, Joints & Seals	Rigid and flexible interfaces providing seals for control surface penetrations, seals between TPS panels, and seals for environmental integrity. Reliable joints and seals designed for maintainability, and if required, easy replacement during normal reflight servicing. Use of CMC hot structures for TPS drives seal temperatures to 2500+F, beyond currently available technology.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-7 (1500F), 1-2 (2500+F)	Yes	5	Representative combined aerothermal, aerodynamic and natural environments cannot be adequately produced in ground facilities or with analyses for advanced seal concepts	Both
TPS, Attachments	Mechanical devices such as struts, brackets, and stanchions for attaching TPS components to a support structure. Robust attachments for UHTCs., CMCs, and Metal Alloy components designed for maintainability.	All new reusable Earth to orbit (ETO) space transportation vehicles	3-7	No	4	Combined aerothermal, aerodynamic and natural environments provided by flight would be very beneficial for development	Both
Aerodynamic Structures, Cold	Support structures for the external TPS defining the vehicle aerodynamics. Nonmoveable wings/fairings/nosecaps that define the vehicle outer mold line. Moveable fin/flaps that provide control surfaces. Simple surfaces with sufficient stiffness for supporting flight weight external TPS.	All new reusable Earth to orbit (ETO) space transportation vehicles	5-7	No	1	Ground demos provide representative environments, with better data quality	
Aerodynamic Structures, Hot	Aerodynamic structures shaped to define the vehicle aerodynamics. Nonmoveable wings/fairings/nosecaps that define the vehicle outer mold line. Moveable fin/flaps that provide control surfaces. Durable smooth surfaces with sufficient aeroelastic performance for flight weight, maintainable designs.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-6	Yes	5	Representative combined aerothermal, aerodynamic and natural environments cannot be adequately produced in ground facilities or with analyses forhot structures	Both
Internal Insulation for Hot Structures	Flight weight internal insulation protecting mechanical, electronic, hydraulic, pneumatic, and propulsion subsystems from the hot structure. Robust insulation with near "zero" inspection and maintainence requirements.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-6	No	1	Ground demos provide representative environments, with better data quality	

Figure A-3: A Sample from a Technology Assessment Database Worksheet

General observations from the database indicate that a number of technologies require some level of flight testing. These include advanced thermal protection systems and hot structures, air-breathing propulsion, flight control software, vehicle recovery, escape and separation systems, and various operational technologies.

The Flight Options Database

The Flight Options Database (Appendix C) was designed to assist users in identifying U.S. flight-test platforms that may be appropriate for their technology demonstrations. These platforms include orbital and sub-orbital vehicles, as shown in the database excerpts in Figure A-4.

Orbital

Vehicle	P/L envelope (ft)	Payload vol (ft3)	Payload (lbs)	Orbit (Nmi)	Inclin (deg)	DDT&E (million $)	OPS COST (million $)	Recovery	Reliability Attempts	Reliability Failures	Embedded Tech	Comments/ Point of Contact
Athena-1	7D x 14L	539	1,892	100x100	28.5		$16	No	3	1		LM
Athena-2	9D x 22L	1400	4,390	100x100	28.5		$22	No	3	1		LM
Improved Athena 2	9D x 22L	1400	5,500	100x100	28.5		~$25 - 30	No				LM
Athena-3	9D x 22L	1400	8,060	100x100	28.5		$30	No				LM
Atlas I	11.975D x 13.75L	1549	12,059	100x100	28.5	~$595	~$77 - 88	No	11	3		LM, out of production
Atlas I	11.975D x 13.75L	1549	10,032	220x220	51.6			No				LM, out of production
Atlas I	11.975D x 13.75L	1549	10,637	220x220	28.5			No				LM, out of production

Solid Motors

Motor	Igniter	Nozzle	Isp (sec)	Total Impulse (vac, lbf-sec)	Total Weight (lbm)	Burn Time (sec)	Thrust (vac, lbf)	Serial #	Stock #	Comments/ Point of Contact
ALGOL III	x	x		7,273,198	31,355	58	104,386		1337-01-ALG-RM03	HAAP
ALGOL III		x		7,273,198	31,355	58	104,386	2898-2		HAAP
CASTOR II	x	x	281	2,307,331	9,748	38	60,063		1337-01-CAS-RM02	HAAP
CASTOR II	x		281	2,307,331	9,748	38	60,063	821		HAAP
CASTOR II		x	281	2,307,331	9,748	38	60,063	797		HAAP
CASTOR II			281	2,307,331	9,748	38	60,063	798M		HAAP

Sub-Orbital

Vehicle	Length (ft)	Diam/width (ft)	Payload vol (ft3)	Payload (lbs)	Flight/Action time	Mach / final height	DDT&E (million $)	Cost per Flt** (million $)	Recovery	Reliability Attempts	Reliability Failures	Embedded Tech	Comments/ Point of Contact
Aries	24	3.7	258	2,000		270 nmi		$1.40	Payload				GSFC
Aries	11.3	3.7	122	3,900		121 nmi			Payload				GSFC
B-52B Aircraft			not internal	50,000	long	0.5 / 7.4 nmi		$.035 - $.075 per hour	Yes				DFRC
Black Brant V	16.7	1.4	26	1,000	26.9 sec	76 nmi		$0.53	Payload	41	1		GSFC
Black Brant X	3:1 ogive	1.4		200	26.9 sec	648 nmi		$0.66	Payload	29	3		GSFC

NASA Balloons

	Average Weight (lbm)	Min. Payload (lbm)	Max. Payload (lbm)	Min. Payload Altitude (Kft)	Max. Payload Altitude (Kft)	Comments/ Point of Contact
Old Design						
11 Light	1,720	700	2,875	132	116	GSFC
11 Heavy	3,200	1,530	6,000	117	102	GSFC
23 Heavy	3,870	3,225	5,375	124	117	GSFC
28 Light	3,330	2,250	3,750	113	128	GSFC
28 Heavy	4,625	3,580	6,000	125	119	GSFC
40 Light	3,925	1,500	3,100	141	135	GSFC

Figure A-4: Samples from the Flight Options Database

Solid motors and NASA balloons are separated from other vehicles in the sub-orbital category. Some solid motors are flight ready while others lack the igniter, nozzle or both, requiring the user to integrate the motor(s) into a test platform suitable for a technology demonstration. This approach may be appropriate if it is determined that traditional sub-orbital vehicles cannot satisfy technology demonstration requirements; however, the complexities of developing a stock motor into a flight vehicle must be carefully considered. On the other hand, a balloon launch assist may be an option for some technology demonstrations where unlimited payload volume is a primary concern.

The database provides basic information to narrow the range of flight options available for technology demonstrations. Data that are common to both sub-orbital and orbital platforms include payload envelope, payload volume, payload delivery capability and platform costs. These are the most pertinent factors the user must consider in assessing flight options. Therefore, the following basic questions must be asked:

- Will a sub-orbital flight satisfy technology demonstration requirements, or is an orbital flight necessary?
- How much payload delivery capability is needed?
- What payload envelope is essential to accommodate the technology?
- How much can I afford to pay for the test platform?

This logical progression will quickly focus the user on appropriate options for the technology demonstration. Also, the “Comments” column shows whether the platform is obsolete or no longer in production.

Note that while some factors cannot be mitigated, others can be traded. The required payload delivery capability, for example, is not flexible, but the standard payload volume afforded by a test platform may provide flexibility. In this case, the user faces the added burdens of designing a non-standard payload fairing and managing the costs associated with its development. It is also important to note that the application of this database presumes that the decision to “fly” has already been determined by the user. No discussion of ground test alternatives is presented here.

Users may consider the possibility of flying as a secondary payload on other test platforms. The main limitation here is that the technology demonstration must not inhibit the mission of the primary payload. A review of the payload envelope will show whether sufficient volume is available to accommodate the technology. In many cases, this envelope represents the fairing size, which may be greater than the limitations established by the launch service provider. The recovery column will indicate “Payload” if the opportunity exists for payload recovery, and will indicate whether the test platform is expendable or may be recovered for another demonstration.

Reliability data have been provided where available. These data indicate the number of failures for the test platform versus the number of flight attempts and should not be confused with mission success. The data include orbital platforms from 1986 through 2000 and sub-orbital platforms from 1981 through February 2002. Embedded technology has been identified where appropriate, as in the case of the X-37. Thermal protection system tiles, integrated vehicle health management diagnostics and lithium-ion batteries are incorporated into the vehicle design. This provides a clear indication that some test platforms are well suited for certain technology demonstrations.

The database does not include information on the environments experienced by the payload during flight, such as thermal, dynamic, acoustic or shock. This information is normally available for orbital platforms and may be obtained in relevant Payload Planners Guides. Because mission-unique analyses are often required for sounding rocket flights to predict the payload environments, descriptions of these environments also have been omitted from the database. Users are encouraged to rely on the Payload Planners Guides or to contact the appropriate organization for guidance on environmental conditions. This step also ensures that technology demonstration decisions are based on the most recent data.

APPENDIX B

Technology Assessment Database (Full Version)

X-Vehicle Team Technology Assessment Worksheet, 5/10/02

Technology Categories	Description/Characteristics	Applications	Reference: approx 2002 TRL	Eventual Flight Demos Required ?	Flight Demo Benefit Index (0-none to 5-significant)	Justification	If Yes, Focused Technology or Vehicle System Demos	Scale Required	Other Requirements	Program Traceability (AFRL, Gen2, Gen3)	Existing RLV Heritage (Shuttle)
Analyses (Rasky)											
Systems Engineering & Architecture Definitions	System engineering and analyses defining architectures, vehicle concepts, vehicle technologies and operations models	All advanced vehicle development programs	5	No	0	Ground activity					
Structures/TPS (Kolodziej, D. Glass, Brunty)											
TPS, Sharp Leading Edges	Small radius (r < 1cm) leading edges for nosetips, wings, and control fins. New, durable sharp leading edge assemblies designed for maintainability.	Enabling for high L/D Earth to Orbit (ETO) and crew return vehicles with improved abort and safety. Enabling for all airbreathing vehicles.	2-5	Yes	5	Representative combined aerothermal, aerodynamic and natural environments cannot be adequately produced in ground facilities or with analyses for sharp leading edge components	Both	Focused Technology - subscales, depending on technology; System Demos - 50% to 100% scale	Representative re-entry profiles, over Mach 20	AFRL, Gen3	None
TPS, Blunt Leading Edges and Nosecaps	Large radius (r > 1 cm) leading edges for for nosetips and wings. Improved, durable blunt leading edge assemblies designed for maintainability.	Medium L/D Earth to Orbit (ETO) cargo and crew return vehicles with Shuttle class abort and safety requirements.	4-6	No	4	Combined aerothermal, aerodynamic and natural environments provided by flight would be very beneficial for development	Both	Focused Technology - subscales, depending on technology; System Demos - 50% to 100% scale	Representative re-entry profiles, over Mach 20	AFRL,	RCC Leading Edge and Nose Cap
TPS, Acreage Surfaces	Flight weight external insulation on large areas of the windward and leeward surfaces that is shaped to define the vehicle aerodynamics. Durable tiles, panels, blankets, or felts designed for maintainability. Typical windward TPS has higher temperature and strength capability than leeward TPS.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-7	No	4	Combined aerothermal, aerodynamic and natural environments provided by flight would be very beneficial for development	Both	Focused Technology - subscales, depending on technology; System Demos - 50% to 100% scale	Representative re-entry profiles, over Mach 20	AFRL,	RSI Tiles, AFRSI Blankets, FRSI Felts
TPS, Joints & Seals	Rigid and flexible interfaces providing seals for control surface penetrations, seals between TPS panels, and seals for environmental integrity. Reliable joints and seals designed for maintainability, and if required, easy replacement during normal reflight servicing. Use of CMC hot structures for TPS drives seal temperatures to 2500+F, beyond currently available technology.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-7 (1500F), 1-2 (2500+F)	Yes	5	Representative combined aerothermal, aerodynamic and natural environments cannot be adequately produced in ground facilities or with analyses for advanced seal concepts	Both	Focused Technology - subscales, depending on technology; System Demos - 50% to 100% scale	Representative re-entry profiles, over Mach 20	AFRL, Gen 3	Gap Fillers, Aerothermal Seals, Thermal Barriers
TPS, Attachments	Mechanical devices such as struts, brackets, and stanchions for attaching TPS components to a support structure. Robust attachments for UHTCs., CMCs, and Metal Alloy components designed for maintainability.	All new reusable Earth to orbit (ETO) space transportation vehicles	3-7	No	4	Combined aerothermal, aerodynamic and natural environments provided by flight would be very beneficial for development	Both	Focused Technology - subscales, depending on technology; System Demos - 50% to 100% scale	Representative re-entry profiles, over Mach 20		Direct Bonded Tiles and Mechanicaly Attached RCC
Aerodynamic Structures, Cold	Support structures for the external TPS defining the vehicle aerodynamics. Nonmoveable wings/fairings/nosecaps that define the vehicle outer mold line. Moveable fin/flaps that provide control surfaces. Simple surfaces with sufficient stiffness for supporting flight weight external TPS.	All new reusable Earth to orbit (ETO) space transportation vehicles	5-7	No	1	Ground demos provide representative environments, with better data quality			Required for system and technology demos of leading edge TPS and acerage TPS	AFRL,	Aluminum Orbiter Airframe
Aerodynamic Structures, Hot	Aerodynamic structures shaped to define the vehicle aerodynamics. Nonmoveable wings/fairings/nosecaps that define the vehicle outer mold line. Moveable fin/flaps that provide control surfaces. Durable smooth surfaces with sufficient aeroelastic performance for flight weight, maintainable designs.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-6	Yes	5	Representative combined aerothermal, aerodynamic and natural environments cannot be adequately produced in ground facilities or with analyses forhot structures	Both	Focused Technology - subscales, depending on technology; System Demos - 50% to 100% scale	Representative re-entry profiles, over Mach 20	AFRL,	RCC Leading Edge and Nose Cap
Internal Insulation for Hot Structures	Flight weight internal insulation protecting mechanical, electronic, hydraullic, pneumatic, and propulsion subsystems from the hot structure. Robust insulation with near "zero" inspection and maintainence requirements.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-6	No	1	Ground demos provide representative environments, with better data quality			Required for system and technology demos of hot aerodynamic structures		
Aerodynamic Structures, Actively Cooled	Aerodynamic structures shaped to define the vehicle aerodynamics, cooled by active thermal transport techniques. Nonmoveable wings/fairings/nosecaps that define the vehicle outer mold line. Moveable fin/flaps that provide control surfaces. Durable smooth surfaces with robust cooling system capability for flight weight, maintainable designs.	All new reusable Earth to orbit (ETO) space transportation vehicles	4-6	No	4	Combined aerothermal, aerodynamic and natural environments provided by flight would be very beneficial for development	Both	Focused Technology - subscales, depending on technology; System Demos - 50% to 100% scale	Representative re-entry profiles, over Mach 20	AFRL, Gen2,	None
Payload Containers	Structures used to interface, support, and deploy payloads. Standardized design to minimize payload integration.	Upper stages of all new reusable Earth to orbit (ETO) space transportation vehicles transporting cargo	6-7	No	0	Ground demos provide representative environments, with better data quality			Required for system demos	Gen2,	Payload Bay
Thrust Structures	Structures used to transfer or support thrust loads including adapters, interstages, intertanks, and linkages. Aluminum alloy and composite structures designed for reliability.	All new reusable Earth to orbit (ETO) space transportation vehicles	5-7	No	0	Ground demos provide representative environments, with better data quality			Required for system demos of propulsion systems and propellant tanks		Boron/Epoxy Thrust Structure for SSMEs and ET/Orbiter Linkage
Propellant Tanks	Structures (mostly cylindrical) used to contain large volumes of propellant at cryogenic temperatures. Aluminum alloy and composite tanks designed for maintainability and reliability	All new reusable Earth to orbit (ETO) space transportation vehicles	5-7	No	4	System flight demos provide critical data on propulsion/structure/TPS integration, very beneficial for development	Only system demos; Technology demos can be performed on the ground	50 - 100%	Representative ascent, on orbit and re-entry trajectories	Gen2	Aluminum Alloy External Tank (SWLT)
Cryo-tank Insulation	Flight weight cryo insulation minimizing cryo-propellant boil-off, ice debris formation, and thermal shock. Robust insulation with near "zero" inspection and maintainence requirements.	All new reusable Earth to orbit (ETO) space transportation vehicles using propellant stored at cryogenic temperatures	5-7	No	1	Ground demos provide representative environments, with better data quality			Required for system demos of cryo-propellant tanks		
Tire/Wheel/Brake system	300 kt tires are required for horizontal takeoff 1.2 M lb vehicles. Those tires currently do not exist.	All new reusable HT ETO vehicles	1	No	1	Ground facilities at NASA GRC and AFRL can validate designs that are developed		100%			

X-Vehicle Team Technology Assessment Worksheet, 5/10/02

Technology Categories	Description/Characteristics	Applications	Reference: approx 2002 TRL	Eventual Flight Demos Required ?	Flight Demo Benefit Index (0-none to 5-significant)	Justification	If Yes, Focused Technology or Vehicle System Demos	Scale Required	Other Requirements	Program Traceability (AFRL, Gen2, Gen3)	Existing RLV Heritage (Shuttle)
Propulsion (McNeal, Klem)											
Main Engine, Rocket	New operable main rocket engines, including H2/LOX and RP/LOC	All new reusable Earth to orbit (ETO) space transportation vehicles	3-6	No	1	Ground demos provide representative environments, with better data quality					
Engine Systems Concepts	Revolutionary concepts that provide 100:1 Thrust/Weight	All new reusable ETO vehicles	1	No	0	Ground demos provide representative environments, with better data quality					
Structural & Turbine Seals	Ramp structural seals that operate up to 2500+F, follow engine sidewall distortions, and survive environmental and cycle conditions. Long life, high temperature, wear resistant turbine shaft seals.	All new reusable ETO vehicles	1-2	Yes	5	Representative combined aerothermal, aerodynamic and natural environments cannot be adequately produced in ground facilities or with analyses for these compoents	Both			Gen3, TBCC	
Valves & Actuators	Highly reliable, highly reusable, lightweight	All new reusable ETO vehicles	5	No	1	Ground demos provide representative environments, with better data quality					
Ducts/Lines Thrust Structure	Lightweight, highly integrated lines and ducts that might also provide thrust structure	All new reusable ETO vehicles	5	No	1	Ground demos provide representative environments, with better data quality					
Combustion Devices	Lightweight, highly integrated, highly reliable, highly reusable, wide throttle combustors with high efficiency	All new reusable ETO vehicles	2	No	1	Ground demos provide representative environments, with better data quality					
Ignition	Lightweight, highly integrated, highly reliable, highly reusable, multi-combustor ignitors	All new reusable ETO vehicles	2	No	1	Ground demos provide representative environments, with better data quality					
Avionics/Control Sys/IVHM	Highly reliable integrated control and sensors with good system model	All new reusable ETO vehicles	2	No	1	Ground demos provide representative environments, with better data quality					
Turbopumps	Lightweight, highly integrated, highly reliable, highly reusable, wide throttle turbopump	All new reusable ETO vehicles	3	No	1	Ground demos provide representative environments, with better data quality					
Main Engine, Airbreathing	New operable, flight weight airbreathing engines	Selected new reusable ETO vehicles	1-4	Yes	5	Representative variable aerodynamic/aerothermal cannot be provided by ground test facilities	Both	TBD	Representative ascent trajectories		
Feedlines, Ducts &Thrust Structure	Lightweight, highly integrated lines and ducts that might also provide thrust structure	All new reusable ETO vehicles	TBD	No	1	Ground demos provide representative environments, with better data quality					
Fluid Transfer	Main engine cross stage fuel transfer	Bimese two-stage ETO vehicles	TBD	Yes	5	Representative variable g-level environment cannot be adequately produced in ground facilities	System; Technology demos can be performed on the ground	TBD	Representative ascent trajectories, with TBD flow rates		
Auxilary Engines	Operable RCS and OMS engines	All new ETO vehicles	TBD	No	2	Ground demos provide representative environments, with better data quality					
High Mach Compressors	Lightweight, highly reliable compressors that withstand Mach 4 temperatures and possibly be exposed to Mach 10 temperatures	Selected new reusable ETO vehicles	1	No	4	Ground demo wil take the system a long way, but flight demonstration would be very beneficial	Both	Both subscale and full scale			
High Integrated Cowls/Inlets	Lightweight, highly integrated inlets that can withstand high temperatures	Selected new reusable ETO vehicles	3	No	4	Ground demo wil take the system a long way, but flight demonstration would be very beneficial	Both	Both subscale and full scale			
Highly Integrated Nozzles	Lightweight, highly integrated nozzles that can withstand high temperatures	Selected new reusable ETO vehicles	3	No	4	Ground demo wil take the system a long way, but flight demonstration would be very beneficial	Both	Both subscale and full scale			
High-Inlet Air Temp. Combustors	Lightweight, highly integrated, highly reliable, highly reusable combustors with high efficiency	Selected new reusable ETO vehicles	1	No	2	Subscale ground demonstration temperatures and conditions can be generated on the ground					
High-Mach Turbines	Lightweight, highly reliable turbines that withstands Mach 4 combustor temperatures	Selected new reusable ETO vehicles	1	No	2	Subscale ground demonstration temperatures and conditions can be generated on the ground					
Software (Cannon, B. Glass)											
GN&C	New adaptive vehicle guidance, navigation and control software	All new ETO vehicles	6-9	Yes	5	Representative variable aerodynammic, and g-level environment cannot be adequately produced in ground facilities	Both	TBD	TBD		
IVHM	Integrated Vehicle health management, diagnostics and prognostics, failure detection and prediction	All advanced vehicle development programs	4-6	Yes	5	Representative faults and nominal vehicle behaviors cannot be adequately produced in ground facilities, leading to eventual false-positives and missed faults	Spot subsystem technology demos, leading to system	Spot demos 10-50%, system near full-scale	Requires avionics, sensors, system-level integration		
Communications	Real-time robust wireless networks of vehicles and ground installations	All advanced vehicle development programs	3-6	Yes	5	Spatial distances, interference, multi-path, network complexities, lightspeed time lags are not ground-reproducible	Spot subsystem technology demos, leading to system	TBD	Affected by balance of on-board vs. ground-based mission control		
Human Interfaces	Crew and ground controller and checkout/maintenance interfaces	All new reusable ETO vehicles	4-6	No	3	Ground simulations are adequate for testing cockpit and flight controller interfaces					

X-Vehicle Team Technology Assessment Worksheet, 5/10/02

Technology Categories	Description/Characteristics	Applications	Reference: approx 2002 TRL	Eventual Flight Demos Required ?	Flight Demo Benefit Index (0-none to 5-significant)	Justification	If Yes, Focused Technology or Vehicle System Demos	Scale Required	Other Requirements	Program Traceability (AFRL, Gen2, Gen3)	Existing RLV Heritage (Shuttle)
Subsystems, Crew Systems & Ops (Klem, Weber, Hite)											
Vehicle Separation Systems	Reliable propulsion start transient and vehicle separation dynamic control at high Q supersonic/hypersonic speeds	Selected new reusable ETO vehicles	4-6	Yes	5	Some demonstration can be done with propulsion wind tunnel models but must be tested on a flight demo to achieve variable aerodynamics and g loading.	System	Both subscale and full scale			
Power	Advanced power systems	All new ETO vehicles	3-5	No	2	Ground simulations are adequate for development					
Avionics	Hardware required for advanced avioncs	All new ETO vehicles	3-5	No	3	Ground simulations are adqaute for development					
Actuators	Advanced electromagnetic actuators for providing vehicle flight control	All new ETO vehicles	3-5	Yes	5	Variable aerodynamic and structural response flight environments required for true actuator response and reliability determinations	Both	Full			
Crew Systems	Hardware for human interfaces and life support	All new crewed ETO vehicles	2-5	No	2	Ground simulations are adequate for development					
Crew Escape	Development of new technologies and systems to enable safer crew escape for new vehicles	All crewed ETO vehicles	2-5	Yes	5	In-order to meet safety goals, flight demonstrations will be required to achieve variable aerodynamic and aerothermodynamic, and g loading environments	System	Close to full			
Recovery Systems	Technologies required to recover the vehicle (parachutes, airbags, tires, brakes…)	All new reusable ETO vehicles	3-6	No	4	Flight environments greatly benefit determination of true technology response and reliability	Both	Full			
Vehicle Turnaround	Advanced checkout, repair and recertification activities on the RLV, including preventative maintainence	All new ETO vehicles	3-6	Yes	5	Full mission environments required for true technology response and reliabilities in order to establish actual turnaround metrics (Shuttle is a good counter example)	System	Subscale			
Range & Ground Ops	Advanced range and flight safety management, including ground power management and monitoring, and ground environmental controls	All new ETO vehicles	3-5	Yes	5	Full mission environments needed to assess limits of new technologies, to meet safety requirements	Both	TBD			
Flight & Launch Ops	Launch operations, fueling, countdown, including operations simulations, training and modelling	All new ETO vehicles	6-9	No	3	Use a technology demonstration testbed -- an "iron rocket", and interpolation from historical data sets					
Crew Ops	Operations to support crew flight activities	All new crewed ETO vehicles	3-6	No	3	Ground simulations arae adequate for development					

APPENDIX C

Flight Options Database (Full Version)

Orbital												
Vehicle	P/L envelope (ft)	Payload vol (ft3)	Payload (lbs)	Orbit (Nmi)	Inclin (deg)	DDT&E (million $)	OPS COST (million $)	Recovery	Reliability		Embedded Tech	Comments/ Point of Contact
									Attempts	Failures		
Athena-1	7D x 14L	539	1,892	100x100	28.5		$16	No	3	1		LM
Athena-2	9D x 22L	1400	4,390	100x100	28.5		$22	No	3	1		LM
Improved Athena 2	9D x 22L	1400	5,500	100x100	28.5		~$25 - 30	No				LM
Athena-3	9D x 22L	1400	8,060	100x100	28.5		$30	No				LM
Atlas I	11.975D x 13.75L	1549	12,059	100x100	28.5	~$595	~$77 - 88	No	11	3		LM, out of production
Atlas I	11.975D x 13.75L	1549	10,032	220x220	51.6			No				LM, out of production
Atlas I	11.975D x 13.75L	1549	10,637	220x220	28.5			No				LM, out of production
Atlas I	9.58D x 12.83L	925	11,375	100x100	51.6			No				LM, out of production
Atlas II	11.975D x 13.75L	1549	14,270	100x100	28.5		~$94	No	10	0		LM, out of production
Atlas II	11.975D x 13.75L	1549	12,145	220x220	51.6			No				LM, out of production
Atlas II	11.975D x 13.75L	1549	12,889	220x220	28.5			No				LM, out of production
Atlas II	11.975D x 13.75L	1549	13,438	100x100	51.6			No				LM, out of production
Atlas IIA	11.975D x 13.75L	1549	15,992	100x100	28.5		~$99	No	19	0		LM
Atlas IIA	11.975D x 13.75L	1549	13,257	220x220	51.6			No				LM
Atlas IIA	11.975D x 13.75L	1549	13,984	220x220	28.5			No				LM
Atlas IIA	11.975D x 13.75L	1549	15,136	100x100	51.6			No				LM
Atlas IIAS	11.975D x 13.75L	1549	17,775	100x100	28.5		~$90 - 105	No	22	0		LM
Atlas IIAS	11.975D x 13.75L	1549	15,920	220x220	51.6			No				LM
Atlas IIAS	11.975D x 13.75L	1549	16,780	220x220	28.5			No				LM
Atlas IIAS	11.975D x 13.75L	1549	16,910	100x100	51.6			No				LM
Atlas IIIA	14D x 16.75L	2578	19,050	100x100	28.5	~$321	~$75 - 80	No	1	0		LM
Atlas IIIB	14D x 13.75L	2117	20,396	100x100	28.5			No				LM
Atlas IV/Agena			8,580				~$70 - 75	No				LM
Atlas IV/Centaur			16,060				~$70 - 75	No				LM
Atlas IV Commercial			39,600				~$80 - 95	No				LM
Atlas V 400	EPF		12,500	100x100	28.5		~$75 - 90	No				LM
Atlas V 500	5 m short		10,300	100x100	28.5		~$90	No				LM
Atlas V 510	5 m short		12,050	100x100	28.5		$90	No				LM
Atlas V 520	5 m short		13,950	100x100	28.5		$95	No				LM
Atlas V 530	5 m short		17,250	100x100	28.5		$100	No				LM
Atlas V 540	5 m short		18,750	100x100	28.5		$105	No				LM
Atlas V 550	5 m short		20,050	100x100	28.5		$110	No				LM
BA-1	11D x 32L	3041	5,720									out of production
BA-2			11,000									out of production
Conestoga 1620			2,123				$18	No				out of production
Conestoga 1679	5.3D x 13.3L	293	3,200	200x200	28.5		~$24 - 25	No				out of production

Orbital												
Vehicle	**P/L envelope (ft)**	**Payload vol (ft3)**	**Payload (lbs)**	**Orbit (Nmi)**	**Inclin (deg)**	**DDT&E (million $)**	**OPS COST (million $)**	**Recovery**	**Reliability Attempts**	**Failures**	**Embedded Tech**	**Comments/ Point of Contact**
Delta II 6920/25	7.2D x 5.6L +	591	7,974	220x220	28.5			No				Boeing
Delta II 6920/25	7.2D x 5.6L +	591	8,107	100x100	50.2			No				Boeing
Delta II 7320			5,896				$35	No				Boeing
Delta II 7420			6,600				~$35 - 40	No				Boeing
Delta II 7920/25	7.2D x 5.6L +	591	11,671	100x100	28.5		~$50 - 60	No				Boeing
Delta II 7920/25	7.2D x 5.6L +	591	10,271	220x220	50.2			No				Boeing
Delta II 7920/25	7.2D x 5.6L +	591	10,770	220x220	28.5			No				Boeing
Delta II 7920/25	7.2D x 5.6L +	591	10,896	100x100	50.2			No				Boeing
Delta III	12.3D x 14.3L	1975	18,280	100x100	28.5		~$75 - 90	No	3	2		Boeing
Delta III	12.3D x 14.3L	1975	16,100	220x220	51.6			No				Boeing
Delta 3/6 GEMs							#REF!	No				Boeing
Delta 3/9 DEMs			17,380					No				Boeing
Delta 4M+			19,008				#REF!	No				Boeing
Delta IV Heavy	15.0D x 48.8L	28055	56,900	100x100	28.5		~$140 - 170	No				Boeing
Delta IV Heavy	15.0D x 48.8L	28055	51,500	220x220	51.6			No				Boeing
Delta IV M	12.3D x 17.3L	2891	18,600	100x100	28.5		0	No				Boeing
Delta IV M	12.3D x 17.3L	2891	17,000	220x220	51.6			No				Boeing
Eclipse Astroliner			4,409				$9	Yes				KST
Eclipse Express			198				~$3	Yes				KST
K-1	11D x 9.6L	912	10,140	100x100	45		$17	Yes				KAC, launched from Australia
K-1	11D x 17.5L	1045	9,480	100x100	45		$17	Yes				KAC, launched from Australia
LLV1	6.5D x 13.75L	456	1,755	100x100	28.5		~$16 - 17	No				LM, out of production
LLV1	6.5D x 13.75L	456	1,410	220x220	51.6			No				LM, out of production
LLV1	6.5D x 13.75L	456	1,555	100x100	51.6			No				LM, out of production
LLV1	6.5D x 13.75L	456	1,600	220x220	28.5			No				LM, out of production
LLV2	6.5D x 13.75L	456	4,390	100x100	28.5		~$20 - 22	No				LM, out of production
LLV2	6.5D x 13.75L	456	3,635	220x220	51.6			No				LM, out of production
LLV2	6.5D x 13.75L	456	3,995	220x220	28.5			No				LM, out of production
LLV2	6.5D x 13.75L	456	4,005	100x100	51.6			No				LM, out of production
LLV3	6.5D x 13.75L	456	5,780	100x100	28.5		~$27	No				LM, out of production
LLV3	6.5D x 13.75L	456	4,900	220x220	51.6			No				LM, out of production
LLV3	6.5D x 13.75L	456	5,300	100x100	51.6			No				LM, out of production
LLV3	6.5D x 13.75L	456	5,355	220x220	28.5			No				LM, out of production
Minotaur	3.3D x 5.0L	44	1,100	100x100	28.5		~$18	No				Orbital
Pathfinder			5,487				~$5	Yes				PR
Pegasus	3.8D x 4.4L +	50 +cone	725	200x200	28.5	~$50+	~$12 - 15	No	9	1		Orbital
Pegasus	3.3L cone		725	200x200	28.5			No				Orbital
Pegasus XL	3.8D x 4.4L +	50 +cone	1,155	200x200	28.5		$14	No	21	3		Orbital
Roton			6,944				$7	Yes				out of production
R210			22				$4					AA
R2150 (PA-2)							~$6					AA

Orbital

Vehicle	P/L envelope (ft)	Payload vol (ft3)	Payload (lbs)	Orbit (Nmi)	Inclin (deg)	DDT&E (million $)	OPS COST (million $)	Recovery	Reliability Attempts	Reliability Failures	Embedded Tech	Comments/ Point of Contact
Scorpius Exodus			14,960				~$10	No				MI
Scorpius Heavy Lift								No				MI
Scorpius Super Heavy Lift								No				MI
Scorpius SR-3			220				~$1	No				MI
STS w/ ASRMs	15.0D x 60.0L	10603	63,863	160x160	28.8	~$1871	~$300 - 400	Orbiter/ASRM	78	1		MSFC, never produced
STS w/ ASRMs	15.0D x 60.0L	10603	43,960	220x220	51.6			Orbiter/ASRM				MSFC, never produced
STS w/ ASRMs	15.0D x 60.0L	10603	51,063	160x160	51.6			Orbiter/ASRM				MSFC, never produced
STS w/ ASRMs	15.0D x 60.0L	10603	56,760	220x220	28.8			Orbiter/ASRM				MSFC, never produced
STS w/ RSRMs	15.0D x 60.0L	10603	51,863	160x160	28.8	~$600	~$300	Orbiter/RSRM				MSFC
STS w/ RSRMs	15.0D x 60.0L	10603	31,960	220x220	51.6			Orbiter/RSRM				MSFC
STS w/ RSRMs	15.0D x 60.0L	10603	39,063	160x160	51.6			Orbiter/RSRM				MSFC
STS w/ RSRMs	15.0D x 60.0L	10603	44,760	220x220	28.8			Orbiter/RSRM				MSFC
STS (OV-102)	15.0D x 60.0L	10603	32,560				$425					MSFC
STS (OV-103/4/5)	15.0D x 60.0L	10603	41,140				$425					MSFC
STS/LFBB	15.0D x 60.0L	10603	55,000					Orbiter/LFBB				MSFC, never produced
Taurus (Darpa Taurus)	4.5D x 9.2L	146	2,684	200x200	28.5		$18	No	3	0		Orbital
Commercial Taurus	5.3D x 8.9L	196	2,860	200x200	28.5		$22	No	2	0		Orbital
Taurus XL	5.3D x 8.9L	196	3,300	200x200	28.5		$24	No				Orbital
Taurus XLS	5.3D x 8.9L	196	3,850	200x200	28.5		$26	No				Orbital
Titan II	9.3D x 22.0L	1494	6,516	100x100	28.5	~$2540		No	10	0		LM
Titan II	9.3D x 22.0L	1494	1,090	220x220	51.6			No				LM
Titan II	9.3D x 22.0L	1494	1,382	220x220	28.5			No				LM
Titan II	9.3D x 22.0L	1494	5,943	100x100	51.6			No				LM
Titan II 3G			5,500				$33	No				LM
Titan II 3G/Star 37							~$35	No				LM
Titan III	11.975D x 26.42L	2975	31,438	100x100	28.5		~$180	No	4	1		LM, out of production
Titan III	11.975D x 26.42L	2975	20,712	220x220	51.6			No				LM, out of production
Titan III	11.975D x 26.42L	2975	22,203	220x220	28.5			No				LM, out of production
Titan III	11.975D x 26.42L	2975	29,294	100x100	51.6			No				LM, out of production
Titan IV / SRM	15.0D x 32.0L	5655	38,119	100x100	28.5		~$350 - 450	No	22	2		LM, out of production
Titan IV / SRM	15.0D x 62.0L	10956	27,109	220x220	51.6			No				LM, out of production
Titan IV / SRM	15.0D x 52.0L	9189	28,928	220x220	28.5			No				LM, out of production
Titan IV / SRM	15.0D x 42.0L	7422	35,660	100x100	51.6			No				LM, out of production
Titan IV / SRMU	15.0D x 62.0L	10956	35,023	220x220	51.6		~$250 - 365	No	8	1		LM
Titan IV / SRMU	15.0D x 52.0L	9189	37,342	220x220	28.5			No				LM
Titan IV / SRMU	15.0D x 42.0L	7422	44,803	100x100	51.6			No				LM
Titan IV / SRMU	15.0D x 32.0L	5655	47,883	100x100	28.5			No				LM
VentureStar			2,750				~$15 - 20	Yes				out of production
X-37	4.0 x 7.0L	88	500	Under review	Under review	Under review	Under review	Yes			TPS, IVHM, Li-ion	MSFC

Sub-Orbital

Vehicle	Length (ft)	Diam/width (ft)	Payload vol (ft3)	Payload (lbs)	Flight/Action time	Mach / final height	DDT&E (million $)	Cost per Flt** (million $)	Recovery	Reliability Attempts	Reliability Failures	Embedded Tech	Comments/ Point of Contact
Aries	24	3.7	258	2,000		270 nmi		$1.40	Payload				GSFC
Aries	11.3	3.7	122	3,900		121 nmi			Payload				GSFC
B-52B Aircraft			not internal	50,000	long	0.5 / 7.4 nmi		$.035 - $.075 per hour	Yes				DFRC
Black Brant V	16.7	1.4	26	1,000	26.9 sec	76 nmi		$0.53	Payload	41	1		GSFC
Black Brant X	3:1 ogive	1.4		200	26.9 sec	648 nmi		$0.66	Payload	29	3		GSFC
Black Brant X	3:1 ogive	1.4		700		243 nmi			Payload				GSFC
Black Brant XI	3:1 ogive	1.4		700	26.9 sec	270 nmi		$0.64	Payload	2	0		GSFC
Black Brant XI	3:1 ogive	1.4		1,200		189 nmi			Payload				GSFC
Black Brant XII	3:1 ogive	1.4		200	26.9 sec	378 nmi		$0.75	Payload	17	1		GSFC
Black Brant XII	3:1 ogive	1.4		500		216 nmi			Payload				GSFC
C-17 Aircraft			internal	150,000	in-flight refuel	0.7 / 7.4 nmi		$.01 - $.035 per hour	Yes				DFRC
DC-8-72 Aircraft			internal	30,000	12 hrs	0.9 / 6.9 nmi		$.006 - $.025 per hour	Yes				DFRC
ER-2 Aircraft			internal	2,600	6 hrs	0.6 / 10.7 nmi		$.006 - $.025 per hour	Yes				DFRC
F-15B Aircraft			not internal	5,000	in-flight refuel	2.0 / 10.7 nmi		$.015 - $.035 per hour	Yes				DFRC
NF-15B Aircraft					in-flight refuel	2.0 / 8.2 nmi		$.020 - $.045 per hour	Yes				DFRC
F-18 Aircraft					in-flight refuel	1.8 / 8.2 nmi		$.015 - $.030 per hour	Yes				DFRC
Joust				500				$2.90	Payload				GSFC
Joust				1,000					Payload				GSFC
MSLS-B				1,450				$7	Payload				LM
MSLS-D				1,450				$9	Payload				LM
NIKE Black Brant				500				$0.50	Payload	65	1		GSFC, obsolete
NIKE Black Brant				1,000					Payload				GSFC, obsolete
NIKE Black Brant II				500				$1	Payload				GSFC, obsolete
NIKE Black Brant II				1,300					Payload				GSFC, obsolete
Nike Black Brant VC		1.8		400		243 nmi			Payload				GSFC, obsolete
Nike Black Brant VC		1.8		900		120 nmi			Payload				GSFC, obsolete

Sub-Orbital

Vehicle	Length (ft)	Diam/width (ft)	Payload vol (ft3)	Payload (lbs)	Flight/Action time	Mach / final height	DDT&E (million $)	Cost per Flt** (million $)	Recovery	Reliability Attempts	Reliability Failures	Embedded Tech	Comments/ Point of Contact
Nike-Tomahawk	6.0-10.0	0.75	2.7-4.4	100	12 sec	200 nmi			Payload	26	1		GSFC, obsolete
Nike-Tomahawk	6.0-10.0	0.75	2.7-4.4	250		119 nmi			Payload				GSFC, obsolete
Orion	6.0-8.3	1.2	6.8-9.4	100		46 nmi		$0.27	Payload	35	0		
Orion	6.0-8.3	1.2	6.8-9.4	200		36 nmi			Payload				GSFC
SR-71 Blackbird			not internal		in-flight refuel	3.2 / 14 nmi		~$15	Yes				DFRC, decommissioned
Super Arcas	2.5	0.375	0.3	10	40.2 sec	50 nmi			Payload				GSFC, obsolete
Super KingAir Aircraft			internal	1,500	8 hrs	0.5 / 5.8 nmi		$.0015 per hour	Yes				DFRC
Shuttle Carrier Aircraft			not internal	277,000		0.6 / 2.5 nmi			Yes				DFRC
Taurus				2,860				$24					Orbital
Taurus-ARPA				2,684				$20					Orbital
Taurus-Nike-Tomahawk	4.5-12.0	0.75	2.0-5.3	70		378 nmi			Payload	15	0		GSFC, obsolete
Taurus-Nike-Tomahawk	4.5-12.0	0.75	2.0-5.3	275		216 nmi			Payload				GSFC, obsolete
Taurus-Orion	6.0-12.5	1.2	6.8-14.1	150		140 nmi			Payload	51	2		GSFC, obsolete
Taurus-Orion	6.0-12.5	1.2	6.8-14.1	500		76 nmi			Payload				GSFC, obsolete
Terrier-Orion	6.0 - 15	1.2	6.8-15	200	25 sec	120 nmi		$0.32	Payload	11	1		
Terrier-Orion	6.0 - 15	1.2	6.8-15	800		50 nmi			Payload				
Taurus-Tomahawk	6.25	0.75	2.8	60	18 sec	319 nmi			Payload	9	0		GSFC, obsolete
Taurus-Tomahawk	6.25	0.75	2.8	130		265 nmi			Payload				GSFC, obsolete
Taurus-XL				3,300				$28					Orbital
Taurus-XLS				4,200				$32					Orbital
Terrier-Black Brant VC	3:1 ogive	1.4		350	26.9 sec	283 nmi		$0.59	Payload				GSFC
Terrier-Black Brant VC	3:1 ogive	1.4		1,100		122 nmi			Payload				GSFC
Terrier-Mallamute								$0.45	Payload	15	0		GSFC
Vista Aircraft			internal		in-flight refuel	0.9 / 8.2 nmi			Yes				USAF
X-36			not internal				$17		Yes				out of production
X-43 A	12	5				7	88	$33.5*	Yes				MSFC

Solid Motors

Motor	Igniter	Nozzle	Isp (sec)	Total Impulse (vac, lbf-sec)	Total Weight (lbm)	Burn Time (sec)	Thrust (vac, lbf)	Serial #	Stock #	Comments/ Point of Contact
ALGOL III	x	x		7,273,198	31,355	58	104,386		1337-01-ALG-RM03	HAAP
ALGOL III		x		7,273,198	31,355	58	104,386	2898-2		HAAP
CASTOR II	x	x	281	2,307,331	9,748	38	60,063		1337-01-CAS-RM02	HAAP
CASTOR II	x		281	2,307,331	9,748	38	60,063	821		HAAP
CASTOR II		x	281	2,307,331	9,748	38	60,063	797		HAAP
CASTOR II			281	2,307,331	9,748	38	60,063	798M		HAAP
ALTAIR III (STAR 20)	x		288	173,886	664	29	5,805	E46		HAAP, replacement parts not available
ALTAIR III (STAR 20)	x		288	173,886	664	29	5,805	P-10*		HAAP, replacement parts not available
ALTAIR III (STAR 20)	x		288	173,886	664	29	5,805	P-11*		HAAP, replacement parts not available
ALTAIR III (STAR 20)	x		288	173,886	664	29	5,805	P-12*		HAAP, replacement parts not available
ALTAIR III (STAR 20)	x	x	288	173,886	664	29	5,805	P-18*		
ANTARES II	x	x		TBD	TBD	TBD	TBD		1337-01-ANT-RM02	
ANTARES III	x	x		837,406	3,076	45	18,156		1337-01-ANT-RM03	
ORBUS 6	x	x	301	1,823,454	8,600	104	18,300	TBD		Bob Hughes, MSFC, 256-544-6624
ORBUS 21	x	x	293	6,268,060	23,960	153	45,000	TBD		Bob Hughes, MSFC, 256-544-6624
ORBUS 21			293	6,268,060	23,960	153	45,000	TBD		Bob Hughes, MSFC, 256-544-6624
STAR 48	TBD	TBD	292	1,303,705	4,721	84	15,430	TBD		Bob Hughes, MSFC, 256-544-6624

NASA Balloons

	Average Weight (lbm)	Min. Payload (lbm)	Max. Payload (lbm)	Min. Payload Altitude (Kft)	Max. Payload Altitude (Kft)	Comments/ Point of Contact
Old Design						
11 Light	1,720	700	2,875	132	116	GSFC
11 Heavy	3,200	1,530	6,000	117	102	GSFC
23 Heavy	3,870	3,225	5,375	124	117	GSFC
28 Light	3,330	2,250	3,750	113	128	GSFC
28 Heavy	4,625	3,580	6,000	125	119	GSFC
40 Light	3,925	1,500	3,100	141	135	GSFC
40 Heavy	5,150	2,000	5,600	135	125	GSFC
New Design						
28X	3,630	2,720	6,500	130	119	GSFC
39 Light	4,023	0	6,000	N/A	127	GSFC
39 Heavy	5,000	4,000	8,000	129	121	GSFC
11 Light	1,720	700	2,875	132	116	GSFC
11 Heavy	3,200	1,530	6,000	117	102	GSFC

APPENDIX D
Study Team Membership

Lt.-Col. Tom Buter	U.S. Air Force Research Labs
Leland Dutro	Marshall Space Flight Center, NASA
Brian Glass	Ames Research Center, NASA
David Glass	Langley Research Center, NASA
Vance Houston	Marshall Space Flight Center, NASA
Mark Klem	Glenn Research Center, NASA
Paul Kolodziej	Ames Research Center, NASA
Col. Sam Liburdi	U.S. Air Force Space Command
Chuck McClinton	Langley Research Center, NASA
Curtis McNeal	Marshall Space Flight Center, NASA
Bill Pannell	Marshall Space Flight Center, NASA
Dan Rasky	Ames Research Center, NASA
Ron Ray	Dryden Flight Research Center, NASA
Phil Sumrall	Marshall Space Flight Center, NASA
Richard Tyson	Marshall Space Flight Center, NASA
Phil Weber	Kennedy Space Center, NASA
Bob Werka	Marshall Space Flight Center, NASA

APPENDIX E
Application of Integration Readiness to Technology Development

The PDA model represents the first formal application of IRL assessment to hardware development; however, examples from technology development show that the concept of integration readiness has been used with successful results in the past. The Saturn 1 program and the Mars Pathfinder program both used elements of IRL assessment during technology and vehicle development. The PDA model recognizes the benefits of this process and formalizes the sequencing of TRLs and IRLs in system development.

The Saturn I program was initiated to develop a space vehicle booster with 1.5 million pounds of thrust using available rocket engines (see Figure E-1). The S-C1 first stage design was based on mature technologies from the earlier Redstone and Jupiter rockets. Using this off-the-shelf hardware saved $60 million and as much as two years in research and development. Atlas and Titan military missiles were considered as possible second stages, but studies found that their size and thrust limited future Saturn growth potential. Work then began on designing the Saturn IV second stage to NASA requirements. Because the S-IV second stage was new and not an integration of existing tanks and proven engines, significant development was necessary to increase its TRL so as not to undermine the high TRL of the first stage. This approach demonstrates IRL theory in practice. The S-IV technology was matured sufficiently for integration and static fire testing just two years after the static fire test of the S-C1 first stage. Important milestones in the Saturn I program are shown in Figure E-2 along with the appropriate IRLs. A continuous iteration cycle, utilizing test data, allowed for improved system analyses to understand Saturn I performance and to predict future Saturn V capability.

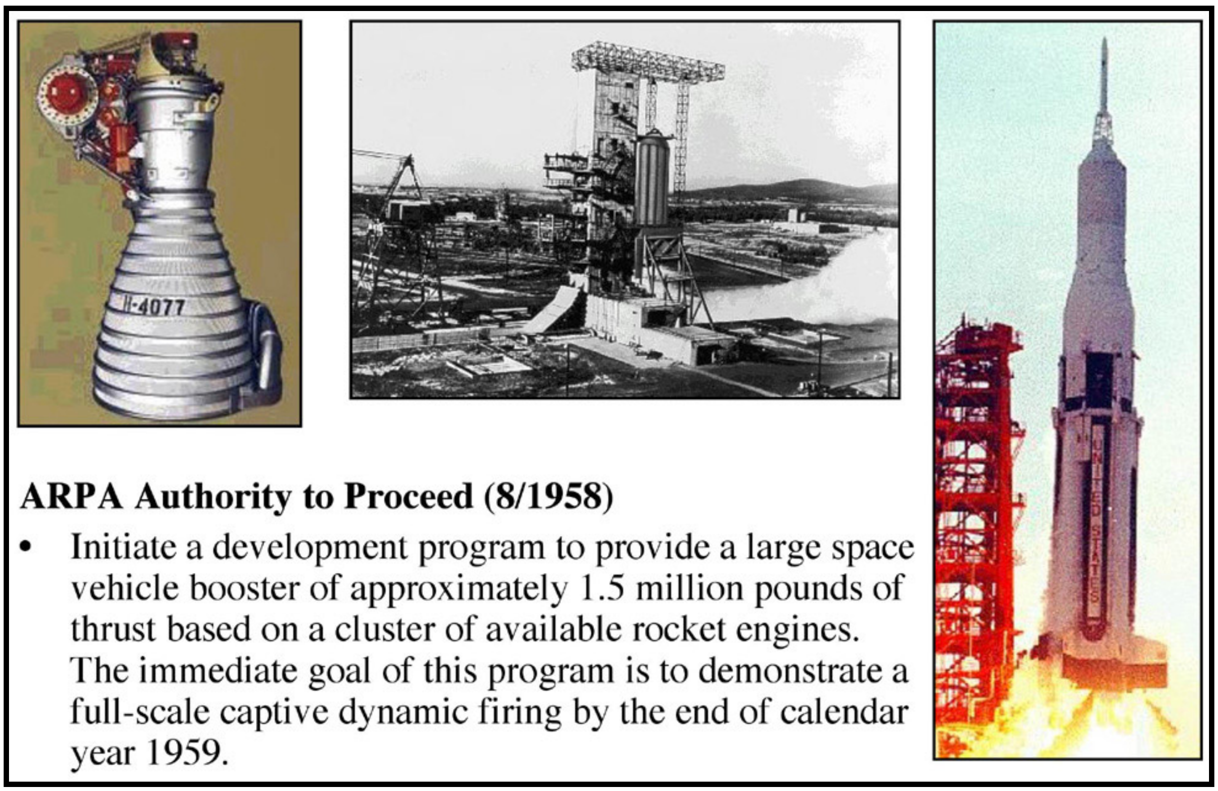


Figure E-1: Saturn 1 Program Description

ABMA studies large clustered-engine booster	4/57
Saturn I proposed by Von Braun	12/57
ARPA issues Authority To Proceed (ATP) with Saturn I	8/58
Redstone Arsenal begins Saturn I design studies	9/58
Contract signed with Rocketdyne for development of the H-1 engine	10/58
First H-1 engine static fire tested at Redstone Arsenal	5/59
Eight H-1 engines static fire together (Saturn 1 transferred to NASA)	4/60
Begin assembly of the first Saturn flight booster	5/60
First integrated Saturn C-1 first stage static fire test	6/60
Saturn I first flight, first stage booster with waterfilled dummy upper stages	10/61
First S-IV second stage static fire test	8/62
First flight of two-stage configuration, S-1 Block II and S-IVB stages	1/64
Saturn SA-7 launch, first closed loop guidance test	9/64
Saturn SA-9 launch of Pegasus 1 payload	2/65
Saturn SA-10 launch of Pegasus 3 payload, final Saturn 1 flight	7/65

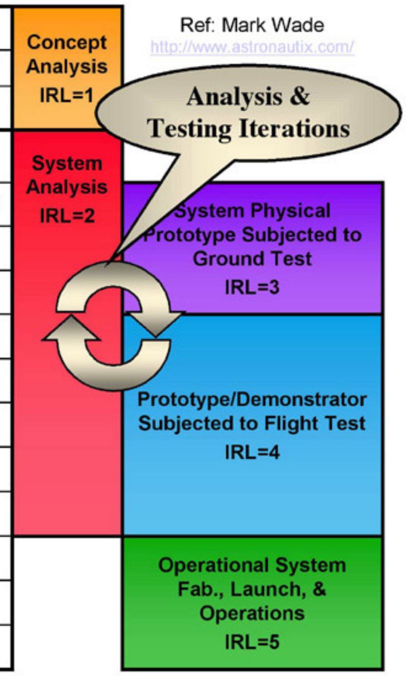
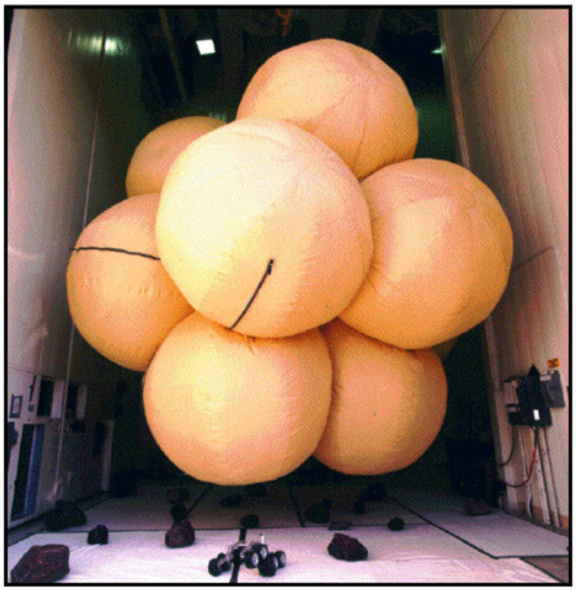


Figure E-2: Application of IRL Assessment to Saturn 1 Development

Mars Pathfinder was a NASA Discovery class mission designed to demonstrate a new generation of rapidly developed, low-cost spacecraft with highly focused science objectives. These constraints forced the designers to adopt a capabilities-driven approach that capitalized on using mature technologies with well-understood capabilities (Figure E-3). Less than five years after the concept took shape, Pathfinder demonstrated a direct entry landing on the planet's surface and deployed a small robotic rover that studied ancient rocks to understand the early Mars environment.

The Pathfinder development strategy focused on two key actions: early concept testing of critical developments and incremental system testing to verify increased functionality. By incorporating these elements of IRL, the program was able to significantly reduce mission risk and cost while delivering a spacecraft in an abbreviated time frame. Lessons learned from this program emphasize the importance of early concept tests, early end-to-end functionality tests, and extensive system/subsystem space qualification and performance tests during all stages of flight operations.

Of the many accomplishments, the airbag landing system that inflated to cushion the lander at impact was one of the most challenging and was successful largely because of extensive testing to verify conceptual and integrated system performance. Important milestones from published reports on the airbag development are shown in Figure E-4 along with the appropriate IRLs. Flight testing (IRL=4) was not required because enough ground testing was conducted at IRL=3 to develop sufficient confidence in airbag performance.



An early 3-lobed airbag configuration

http://mars.jpl.nasa.gov/MPF/mpf/mpfairbags.html

Later configuration undergoing drop test at simulated impact site

Figure E-3: Mars Pathfinder Program Airbag Description

Proof of Concept (POC) impact test of 0.38 scale airbag (3 lobe) at Sandia High Altitude Chamber (HAC)	5/93	Concept Analysis IRL=1	System Physical Prototype Subjected to Ground Test IRL=3
POC drop test at Sandia Coyote Canyon Facility - evaluate structural integrity and demonstrate system feasibility	8/93		
Sandia computer model developed to analyze the pneumatic performance and rigid-body dynamics during ground impact	11/93	System Analysis IRL=2	
Award contract to ILC Dover Inc. to begin full scale development	4/94		
POC landing test (6 lobe) at Sandia - demonstrate performance and validate computer models for analysis and design	9/94		
POC full scale airbag retraction at Mars ambient T,P performed at JPL	9/94		
Switch from Kevlar to Vectran fabric to improve handling and folding capability	9/94		
Component Level Rock Impingement (CLRI) test of abrasion layer by dropping lava rocks onto fabric samples			
CLRI test of bladder rupture by pressing a sharp rock into an inflated dome			
System Level Rock Drop (SLRD) tests of abrasion layer by dropping full-scale airbags onto sharp rocks in a Mars like near-vacuum environment at NASA Plum Brook	6/95		
Structural analysis of the landing event using the Rockwell DYNA code			
Gas generator firings demonstrate deployment in 1.5 sec and data used to assess and correlate the thermal model	No IRL=4		
Full Scale Development (FSD) testing begins	10/95		Operational System Fab., Launch, & Operations IRL=5
Final qualification FSD test demonstrating inflation at -80 C and successful drop tests at NASA Plum Brook	6/96		
Launch	12/96		

Figure E-4: Application of IRL Assessment to Mars Pathfinder Airbag Development